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Comparative Analysis Between a Capillary Tube and an Electronic Expansion Valve in a Household Refrigerator

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COMPARATIVE ANALYSIS BETWEEN A CAPILLARY TUBE AND AN ELECTRONIC EXPANSION VALVE IN A HOUSEHOLD REFRIGERATOR

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ABSTRACT

This study compares the performance characteristics of a household refrigerator equipped with an Electronic Expansion Valve (EEV) with those with a capillary tube. A 513-liter top-mount refrigerator, originally equipped with a capillary tube, was retrofitted with a Pulse Width Modulated (PWM) expansion valve and extensively tested. Comparative analyses were performed based on standardized pull-down and energy consumption tests, carried out at three ambient temperatures (18°C, 32°C and 43°C) and with three compressor speeds (2000 rpm, 3600 rpm and 4500 rpm). It was shown that the EEV system showed better performance in terms of energy consumption, as compared with the capillary tube system, only at high cooling loads (ambient temperature of 43°C) and at low cooling capacities (compressor speed of 2000 rpm). For a wide range of operating conditions the pull-down times of both systems were kept within a difference band of ± 3%.

1. INTRODUCTION

A capillary tube (CT) has no moving parts, nothing to wear out, and is simple and inexpensive. It allows the pressures in the system to equalize during the off cycle, thus reducing the compressor starting torque requirements. On the other hand, the capillary tube cannot be adjusted according to changing load conditions and requires the refrigerant charge to be held within close limits. Moreover capillary tubes are easily clogged by small particles that can affect the system efficiency or even interrupt its operation (Marcinichen, 2001). An Electronic Expansion Valve (EEV) is more advanced, having a proportional feed-back action control mechanism that adjusts the valve opening to maintain a constant evaporator superheat under all test conditions. On the other hand, the EEV has movable parts and is more expensive.

This study explores the benefits of using an EEV as a refrigerant flow regulating device in a household refrigerator. A refrigeration system, originally equipped with a capillary tube, was retrofitted with a Pulse Width Modulated (PWM) expansion valve. Standardized pull-down and energy consumption tests, with both compartments loaded, were then carried out in order to compare the performance characteristics of the CT and EEV systems.

In a previous study, Marcinichen *et al*. (2004) carried out tests with the same appliance but with the compartments unloaded. The pull-down test results were not entirely conclusive, but the energy consumption test results gave a clear indication that the CT system saved energy. It was also shown that the EEV system became more efficient at higher ambient temperatures.

Based on these results, a second set of experiments was planned, this time with both compartments (freezer and fresh food) loaded. The idea was to increase the cooling load in an attempt to identify the benefits of the EEV system over the CT system. The tests were carried out at three ambient temperatures (18°C, 32°C and 43°C) and with three compressor speeds (2000 rpm, 3600 rpm and 4500 rpm).

This paper firstly introduces the EEV operation characteristics and gives some recommendations regarding its installation. Secondly, the CT and EEV systems test results are presented and discussed. Finally, a comparative analysis exploring the performance characteristics of both systems is carried out.

It is worth mentioning that related studies reported in the open literature (Tassou and Al-Nizari, 1991; Aprea and Mastrullo, 2002; Choi and Kim, 2002, 2003), are all focused on refrigeration systems with cooling capacities much higher than those considered herein.

2. ELECTRONIC BOARD / EXPANSION VALVE SYSTEM

2.1 Characteristics of the EB/EEV System

The electronic expansion valve (EEV) is basically composed of a reed valve, an orifice and an electric coil. At certain time intervals, voltage is applied to the coil of the valve actuator, causing current to flow in the coil and creating a magnetic field that opens the valve. Voltage is applied for a time interval (pulse width) proportional to evaporator superheat.

The electronic board (EB) operates based on three parameters, namely: pulse period (T), maximum duty cycle (DM) and duty cycle (D). These parameters can vary according to the system cooling capacity and should be appropriately adjusted to guarantee a proper operation of the valve. The refrigerant mass flow rate through the valve is a function of the orifice size and of the maximum duty cycle. A valve with a particular orifice size can therefore be applied in installations having a range of cooling capacities by electronically setting the maximum valve duty cycle to match the capacity of each installation.

The valve considered in this study differs from others using the same principle as follows: i) control down to very low mass flow rates, ii) low power consumption (~0.5W), iii) extremely long life (~30 years), iv) small size and weight, v) valve closes during compressor-off (minimizing on-off losses), vi) stable operation without electronic compensation and vii) control at low superheat (3^oC typical).

2.2 EEV installation

As shown in Figure 1, the EEV is installed in the liquid line, at the inlet of the evaporator. To avoid possible anomalies and/or losses of efficiency care should be taken during the EEV installation as follows: i) installation of a suction line to liquid line heat exchanger to guarantee the presence of liquid at the inlet of the valve, ii) installation of two accurate thermistors, one in thermal contact with the evaporator inlet and the other in thermal contact with the suction line near the point where the suction line leaves the freezer compartment, and iii) installation of a liquid accumulator at the outlet of the evaporator to stabilize the superheat signal.

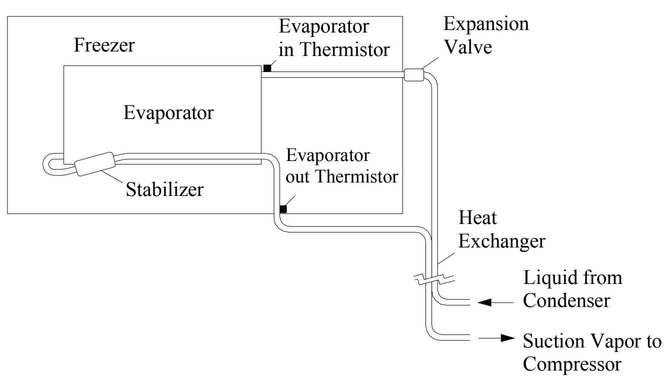

Figure 1: EEV installation

3. CT SYSTEM

The analysis presented herein was carried out with a 513-liter top-mount refrigerator, in which the compressor is on-off controlled by the fresh-food compartment temperature, while a thermo-mechanical damper is used to set the freezer temperature.

3.1 Instrumentation

The compressor of the original system was replaced by a variable speed compressor of similar capacity. A Coriolis mass flow rate measurement device was installed at the compressor discharge point, with little effect on the system refrigerant charge due to its low internal volume. The evaporation and condensation pressures were measured using absolute pressure transducers. The refrigerant temperatures were measured by T-type thermocouples attached to the tube walls. The air temperatures were also measured by T-type thermocouples, embedded in copper cylinders to provide good thermal contact with the surrounding air (ISO 7371, 1985).

The ambient temperature was taken as the arithmetic mean of the readings of three thermocouples installed in the central plane and at 15 cm from the lateral and front walls (ISO 7371, 1985). The refrigerator was positioned at 30 cm from the side walls and at 12 cm from the back wall, following the recommendations of the standard ISO 7371(1985). The appliance voltage, current and input power were measured by specific transducers. The output signals from the transducers and thermocouples were recorded through a computerized data acquisition system.

3.2 Tests Results

The original system, loaded and charged with 106.7 grams of HFC-134a, was tested under the test conditions given in Table 1. During the energy consumption tests the freezer compartment was loaded with tylose packages (ISO 8561, 1997), while the fresh food compartment was kept empty. On the other hand, the pull-down tests were carried out with both compartments loaded, the freezer with 16 pots filled with 1 liter of water and the fresh food with 45 350 ml beverage cans strategically distributed.

Table 1: Test conditions for the CT system

Test	Temperature [ºC] / Speed[rpm]
Pull-down	18 / 3600
	32 / 3600
	43 / 3600
Energy consumption	18 / 3600
	32 / 2000, 3600 and 4500
	43 / 3600

The pull-down time was defined as the time required to reach an average pot temperature of 3^{o}C. Table 2 shows that the pull-down time increased as the ambient temperature increased, as expected.

Table 2: Pull-down times – CT system

Ambient temperature [^{o}C]	Pull-down time [h]
18.1 ºC	1h 59min
32.0 ºC	4h 00 min
43.1 ºC	5h 43min

The energy consumption tests were carried out following the recommendations of the standard ISO 8561 (1997), which specifies the reference temperatures of -18^{o}C and 5^{o}C for the freezer and fresh food compartments, respectively. Two tests were carried out under each of the test conditions given in Table 1, one with the thermostat and damper set to generate compartment temperatures above the reference values and the other to generate compartment temperatures below the reference values. The energy consumption at each reference temperature was obtained by linear interpolation. The highest value was taken as the appliance energy consumption and is given in Table 3. It should be pointed out that the energy consumption values given below relate only to the compressor power.

Table 3: Energy consumption – CT system

Test condition	Energy consumption [kWh/month]
18 ºC / 3600 rpm	23.41
32 ºC / 2000 rpm	38.89
32 ºC / 3600 rpm	46.57
32 ºC / 4500 rpm	54.45
43 ºC / 3600 rpm	76.13

As expected, the energy consumption increased both with the compressor speed and with the ambient temperature.

4. EEV SYSTEM

Before installing the EEV in the refrigeration system some modifications to the electronic board were required, as follows: i) implementation of a control algorithm to equalize the system pressures during compressor-off periods, ii) implementation of a control algorithm to open the EEV at the compressor start-up (no superheating), iii) implementation of trimpots for adjusting T and DM and iv) implementation of a voltage signal proportional to D/DM.

Modifications to the household refrigerator were also required before the installation of the EEV, all of them being described in section 2.2. A liquid line-suction line heat exchanger (1.20 m in length), an EEV (orifice diameter of 0.65mm), a superheat stabilizer (volume of 50 cm^3) and two thermistors (10kΩ at 25ºC, class 0.1ºC) were all installed in the refrigeration system.

4.1 Determination of the refrigerant charge and the DM Parameter

Due to the modifications introduced into the system, with the consequent enlargement of its internal volume, a new refrigerant charge had to be determined. The refrigerant charge tests were carried out with a pulse period (T) of 2.0 s, as recommended by the valve manufacturer, at an ambient temperature of 32 ^oC and with a compressor speed of 3600 rpm. For each refrigerant charge the DM value was adjusted until the superheat at the evaporator outlet reached a minimum value. The test results with five different refrigerant (HFC134a) charges of 109.9g, 120.1g, 130.8g, 141.0g and 151.1g are illustrated in Figures 2 and 3.

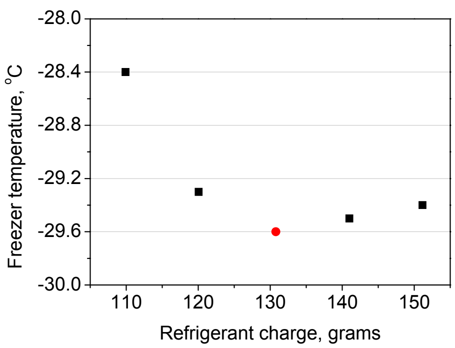

Figure 2: Freezer temperature vs. charge

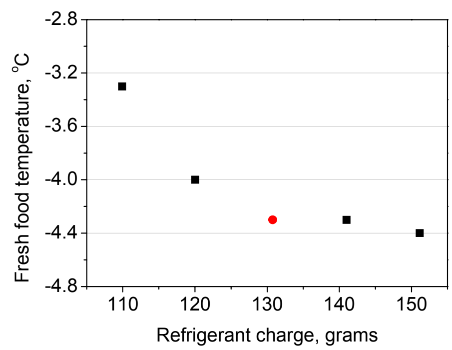

Figure 3: Fresh food temperature vs. charge

It was observed that the refrigerant mass flow rate, the evaporation pressure, the compressor power and the compartment temperatures remained practically constant above a refrigerant charge of 130.8 grams. This value was thus adopted as the refrigerant charge for the EEV system.

4.2 Test Results

The EEV system, loaded and charged with 130.8 grams of HFC134a, was submitted to standardized pull-down and energy consumption tests, under the test conditions given in Table 1. The parameters T and DM were set as 2 s and 80% (1.6 s) during the pull-down tests, respectively. The DM value was the maximum allowed by the electronic board, and was chosen to maximize the refrigerant mass flow rate and to minimize the pull-down time. The test results are shown in Table 4.

Table 4: Pull-down times – EEV system

Ambient temperature [^{o}C]	Pull-down time [h]
18.8 ºC	1h 55min
32.6 ºC	3h 56min
42.8 ºC	5h 51min

Table 4 shows that the pull-down time of the EEV system increases as the ambient temperature increases, following a pattern quite similar to that observed with the CT system.

The DM parameter was adjusted for each test condition during the energy consumption tests. The adopted value was that which provided a minimum superheat at the evaporator outlet, under steady-state conditions and with the system unloaded. The adjusted values are shown in Table 5.

Table 5: Maximum duty cycle

Test condition	Maximum duty cycle [s]
18 ºC / 3600 rpm	1.10
32 ºC / 2000 rpm	1.30
32 ºC / 3600 rpm	1.30
32 ºC / 4500 rpm	1.30
43 ºC / 3600 rpm	1.55

The procedures described for the energy consumption tests with the CT system were also adopted for the EEV system. The test results are given in Table 6.

Table 6: Energy consumption – EEV system

Test condition	Energy consumption [kWh/month]
18 ºC / 3600 rpm	26.85
32 ºC / 2000 rpm	37.63
32 ºC / 3600 rpm	50.90
32 ºC / 4500 rpm	58.74
43 ºC / 3600 rpm	73.79

As expected the energy consumption of the EEV system increases as the ambient temperature and the compressor speed increase. The energy consumption of the EB-EEV pair was also individually measured and was found to be 1.42kWh/month.

5. CT VERSUS EEV SYSTEM

The pull-down times of the CT and EEV systems for three ambient temperatures are compared in Table 7 and Figure 4. As can be seen the pull-down times of both systems were kept within a difference band of ± 3%. It can also be observed that the pull-down time of the EEV system was lower than that of the CT system at low ambient temperatures and higher at high ambient temperatures.

Table 7: Pull-down times – comparative analysis

Temperature [ºC]	Pull-down time [h]	
	CT system	EEV system
18.0	1h 59min	1h 55min
32.0	4h 00min	3h 56min
43.0	5h 43min	5h 51min

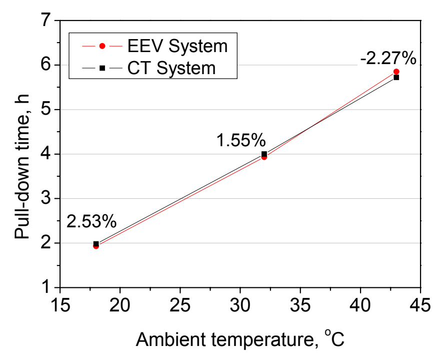

Figure 4: Pull-down times – comparative analysis

Figure 5 shows the evaporator superheat at an ambient temperature of 43°C, for the CT and EEV systems. As can be seen the initial cooling rate of the EEV system exceeded that of the CT system because, as the entire cold space was initially at ambient temperature, the EEV started with a superheat much higher than the set point, so that the control maintained the maximum duty cycle. As the cold space temperature decreased, the superheat also decreased and after around 2 hours the superheat values of the two systems became equal. Thereafter the CT system was more effective, reaching an optimum point after around 5 hours, when the mass flow rate through the capillary tube matched the evaporator heat transfer, so that the evaporator superheat was zero. It is worth mentioning that the evaporator superheat of the EEV system was controlled by a particular control algorithm furnished by the valve manufacturer, which was not investigated in this study.

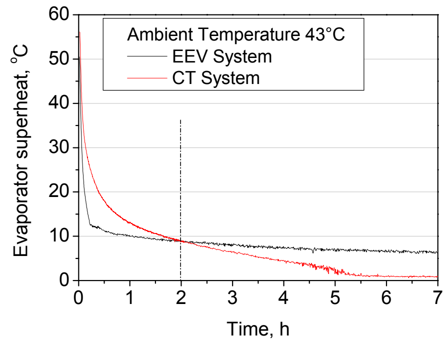

Figure 5: Evaporator superheat

Table 8 shows the average cooling capacities of the two systems during the pull-down tests. As expected the cooling capacities were directly related to the pull-down times (see Table 7).

Table 8: Cooling capacities – comparative analysis

Temperature [ºC]	Cooling capacity [W]	
	CT system	EEV system
18.0	214.8	227.3
32.0	215.8	220.3
43.0	248.2	221.8

The energy consumption test results are summarized in Table 9 and in Figures 6 and 7. The percentage values shown in Figures 6 and 7 represent the difference in energy consumption between the two systems in relation to the CT system.

Table 9: Energy consumption – comparative analysis

Test conditions	Energy consumption [kWh/month]	
Temperature [ºC]/ Speed [rpm]	CT system	EEV system
18 / 3600	23.41	26.85
32 / 2000	38.89	37.63
32 / 3600	46.57	50.90
32 / 4500	54.45	58.74
43 / 3600	76.13	73.79

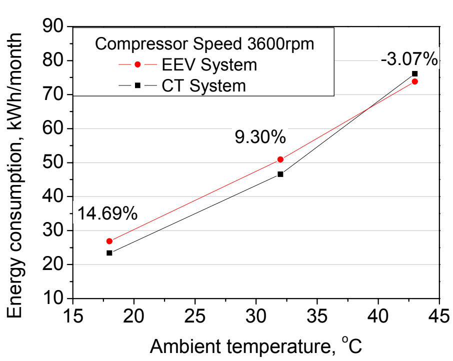

Figure 6: Energy consumption vs. ambient temperature

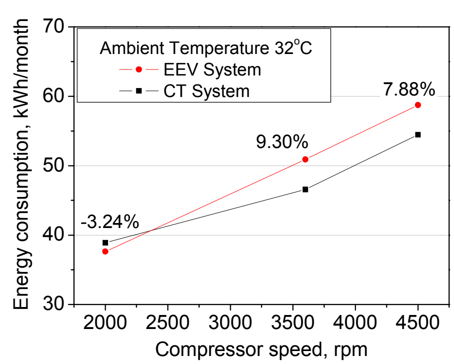

Figure 7: Energy consumption vs. compressor speed

It can be observed that the EEV system energy consumption is only lower than that of CT system at high cooling loads (ambient temperature of 43°C) and at low cooling capacities (compressor speed of 2000 rpm).

Figures 8 and 9 display the evaporator superheat during a compressor cycle at 32°C and 4500 rpm for the EEV and CT systems, respectively.

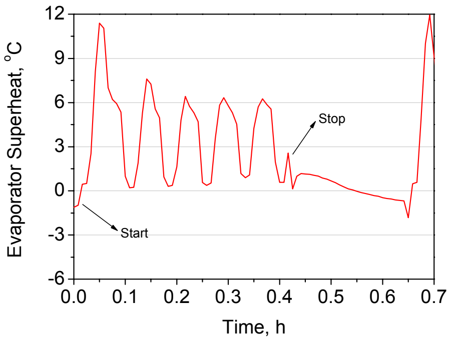

Figure 8: Evaporator superheat – EEV system

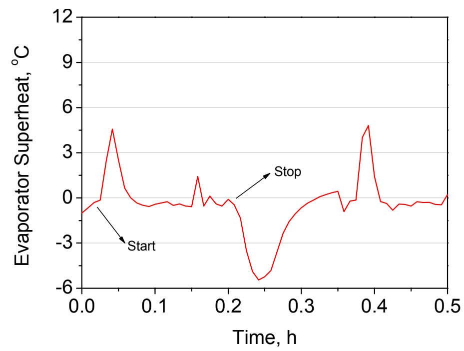

Figure 9: Evaporator superheat – CT system

As can be seen the evaporator superheat was not effectively controlled by the electronic board of the EEV system, which generated an average superheat value (4.0°C) higher than that of the CT system (0.2°C). This means that the refrigerant mass flow rate through the capillary tube better matched the evaporator heat transfer than that through the electronic expansion valve. As a consequence the cooling capacity and the energy consumption of the EEV system were lower and higher than those of the CT system, respectively.

It should be pointed out that the EEV system performance can be optimized by implementing a more efficient control algorithm to adjust the EEV opening to maintain a low and constant superheat under all test conditions. Part of the inefficient superheat control found in this study may also be due to the valve orifice size, which might be too large for the appliance under test.

6. CONCLUSIONS

The pull-down time and the energy consumption of a 513-liter top-mount refrigerator equipped with a capillary tube and with an electronic expansion valve were compared in this study.

It was found that the energy consumption of the EEV system was only lower than that of the CT system at higher cooling loads and at lower cooling capacities. For all other test conditions the CT system saved energy. It is worth mentioning that the EEV system performance was directly related to instabilities in the superheat control, and this may be partly due to the control algorithm and partly to the valve orifice size used.

The pull-down times of the EEV system tested at 18°C and 32°C were lower than those of the CT system. An opposite scenario was observed for the test carried out at 43°C. It should be mentioned that the pull-down times for both systems were kept within a difference band of ± 3%.

One of the primary limitations of this study was that the data were taken for a particular household refrigerator. Similar analyses should be carried out with other refrigerators currently in use, especially those with a much higher cooling load such as the beverage coolers.

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